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AC LOSS IN FLAT TRANSPOSED SUPERCONDUCTING CABLE

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I. Introduction

Superconducting magnets for pulsed accelerators are preferably operated at 3000 A or more to reduce inductance. To keep the hysteresis loss as small as possible, the filament diameter of composite Superconductor should be less than 10μ (the smaller the better). At a field of 5T, such a single filament of NbTi will carry only about 100 mA. We have to put $10^4 \sim 10^5$ filaments in parallel to make a conductor with a capacity of at least 3000 A. A monolithic wire with 10^4 filaments is now commercially available. The coupling between filaments becomes stronger as its number is increased; firstly because it is impossible to have a small twist pitch (minimum twist pitch ~ 5 x wire diameter) and secondly because of the self-field instability.

To overcome these problems, composite superconductors (strands) with a large number of filaments and with an overall diameter less than about 1 mm, are cabled or braided together. These wires have been developed at Rutherford Lab and BNL. The strands should be fully transposed to avoid the self-field instability, and separately insulated from each other to reduce interstrand coupling. But the insulated conductor is usually less stable in an actual magnet than the metal filled conductor, probably because of the movement of the strands. The latter conductor is better cooled and has a larger specific heat capacity but the coupling between strands at the changing field can result in a large AC loss and reduces stability. In view of the stability, the metal filled conductor should be used especially in a pulsed magnet with a low duty cycle. A compromise between two requirements is to coat the strands with a high resistance metal, e.g. with cupro-nickel sheath.

Magnetization of superconductor is the main part of AC loss in a pulsed magnet. For the estimation of the AC loss in a magnet and also for an investigation of a quality of the conductor itself, we measured the magnetization of wire at varying magnetic fields.

II. Brief Theoretical Survey

Losses in superconducting cables, when exposed to time varying magnetic field, have several origins:

(i) Hysteresis loss in superconducting filaments,

(ii) Self-field loss,

(iii) Eddy current loss in the normal matrix of a single strand.

(iv) Eddy current loss caused among different strands.

The self-field loss is generally known to be very small compared with the other terms in the fully transposed cable.

To derive the practical loss formula, we have different approaches.[1] According to M.N. Wilson et al[2][3], the magnetization of the cable can be given in MKS unit as follows.

$$M = Mo \left\{ 1 + \frac{1}{\lambda J_e d} \left(\frac{\dot{B}\ell^2}{\rho} + \frac{\dot{B}_\perp L^2}{\rho_a} \left[\frac{4}{5}\alpha^2 + 1 \right] + \frac{\dot{B}_{\parallel} L^2}{\alpha^2} \frac{3}{4} \right) \right\} \quad (1)$$

where the notation is as follows,

M_o = the magnetization due to all filaments: $\dfrac{2k\mu_o \lambda J_c d}{3\pi}$

λ = filling factor of the filament in the composite

J_c = critical current density in the superconductor

d = filament diameter

$\dot{B}$ = field changing rate

$\dot{B}_\perp$ = component of $\dot{B}$, perpendicular to the flat face

$\dot{B}_{\parallel}$ = component of $\dot{B}$, parallel to the flat face

k = compaction density of cable.

ρ_e = effective transverse resistivity across composite

ρ_a = average transverse resistivity across cable

α = aspect ratio of cable

4ℓ = twist pitch of filaments

$4L$ = transposition pitch of strands

For a two component composite and the uniform arrangement of filaments, ρ_e can be given as $\rho_e = \frac{\pi}{3}\frac{\omega}{d}\rho_\omega$, where ω is the thickness of normal metal between each filament and ρ_ω is its resistivity.

Here the second term arises from the coupling between filaments inside a strand and the other two terms from the coupling between the strands. In the latter terms, the dominant coupling is due to interconnection between crossing strands rather than the overall parallel current along wire. The fourth one is negligible compared to the former one.

The AC loss per cycle is given by integrating MdH over a complete cycle. In a case of linear ramp, it can easily be given:

$$Q \simeq \frac{4}{3\pi} kJ_c \lambda dB_{max} + \frac{4}{3\pi} kJ_c \lambda dB_{max} \left\{ \frac{\dot{B}\ell^2}{\rho_e} + \frac{\dot{B}_\perp L^2}{\rho_a}\left(\frac{4}{5}\alpha^2 + 1\right) \right\} \qquad (2)$$

where J_c is assumed to be constant all over the magnetic field (Bean model)[4] and the last term in Eq.(1) is neglected. The hysteresis loss (the first term in Eq. (2)) does not depend on $\dot{B}$ and $\dot{B}$ dependence comes from the coupling between filaments and between strands.

III. Experimental Method

The usual magnetization measurements were made using the standard electrical technique. The schematic block diagram is shown in Fig. 1. For this purpose, the bias magnet was constructed from IGC 7-strand cable. Its inner diameter is $3\frac{1}{8}$ inches and its height is 5.5 inches. It gives 20 kG at the central 3 inch region with an exciting current of 1740 Amp. A sample is put in one of a pair of search coils, which is located in a homogeneous part of the bias solenoid. These search coils are connected to an individual potentiometer, and the potentiometers are adjusted to have no signal without sample. The difference signal, with the sample placed in one of search coils and with sweeping field, is integrated by an analogue integrator and sent to the Y axis of the X-Y recorder. The signal proportional to the solenoid current is displayed on the X axis. The area of the loop obtained on the X-Y chart represents the AC loss of the sample. When the analogue integrator is used, its drift causes an error, and the calculation of the area of M-H loop is very troublesome.

We developed an on-line system.[5] The balanced signal and the current signal of the solenoid are supplied to Tektronix Digital Processing Oscilloscope, and then digitized at 512 points. These data are sent to a PDP-11 computer, multiplied and integrated over the entire cycle. In this way we can quickly obtain final results, according to the following equation

$$\oint H\cdot\dot{M}dt = \oint HdM = -\oint MdH\,. \tag{3}$$

To avoid end effects and to investigate coupling between strands, it is necessary to use a sample whose length is much longer than its twist and transposition pitch. Thus we used a coiled shape sample, usually 20 inches long. Also a winding radius should be large enough so that soldering between strands might not be broken. This fact requires us to use search coils with a large diameter, which causes them to pick up big, unnecessary signals.

To investigate the field orientation dependence of the coupling of strands we wound two kinds of coil. One is a normal cylindrical coil with a diameter of 2 inches, where the external field is parallel to the flat face of the cable. The other is a squashed coil, which has a long straight section enough to investigate the interstrand coupling. The external field is perpendicular to the flat face of the cable. There may be some damage, but we can know the difference between both cases.

In all measurements, a positive triangular current form with flat top is used. The ramp rate dependence at a constant maximum magnetic field, and the maximum field dependence at a constant sweep rate are measured. Some specifications of the measured cables are listed in Table I.

IV. Results and Discussions

4.1 MCA 17 Cable

The normalized ramp rate dependence of AC loss is shown in Fig. 2. The values at $\dot{B} = 0$ correspond to the hysteresis losses. The losses increase linearly in the region of small $\dot{B}$, but seem to saturate at the high values of $\dot{B}$.

For the unsoldered sample, the loss doesn't strongly depend on the field orientation, compared with the soldered one. But for the soldered one, it increases rapidly as the sweep rate does for the perpendicular field. For the parallel field, it only shows a weak dependence. This fact means that the increase of AC loss mainly arises from the eddy current between strands, not filaments.

In order to verify this fact we cut the soldered sample such that its length is smaller than the transposition pitch: 0.5 inch. The obtained ramp rate dependence for the perpendicular field is shown in Fig. 2. The dependence got much weaker. This fact again confirms that increase of AC loss for the perpendicular field is due to the eddy current between strands.

In Table II, we listed the doubling $\dot{B}(\dot{B}_d)$. We assume the rate dependence for the parallel field is due to the coupling between filaments (this is roughly right for a wire with a large aspect ratio). Then we can calculate ρ_e from the obtained $\dot{B}_d$ (parallel). Using this ρ_e and $\dot{B}_d$ (perpendicular), ρ_a can easily be derived from Eq. 2.

The values of ρ_e and ρ_a obtained in this way are also listed in Table II. The magnitude of ρ_e is pretty large compared with pure copper resistivity. In these cables, space between five filaments is very close (5μ) and it is not easy to estimate the precise effective resistivity. Wilson et al[5] found the apparent transverse resistivity of matrix in a composite wire to be $6\sim34\times10^{-8}$ Ω·cm when the distance between filaments ranged from 17μ to 3μ.

The maximum field dependence at constant ramp rate is shown in Fig. 3. At around 1 kG there is a bending point, which corresponds to the field where the flux completely penetrates into the filament (what is called the saturation field: $B_s = \frac{1}{2}\mu_0 J_c d$). The loss per cycle is proportional to $B_{max}^2 \sim B_{max}^3$ for $B_{max}<B_s$, and proportional to B_{max} for $B_{max}>B_s$, respectively. This result corresponds to the observation that in the high field, the magnetization loop gets flat as shown in Fig. 4.

The observed dependence on B_{max} (qualitatively) agrees with that predicted from the Bean theory[4], although the assumption of constant J_c over the entire external field is not right in an actual case. In the above cases, the starting field is 0 kG. The maximum field dependence for the initial field of 9 kG (corresponding to 200 GeV) was also obtained and is shown in Fig. 3. The results show that the loss is almost proportional to $(B_{max}-9)$kG as expected from the dependence for 0 kG.

4.2 MCA 23 Cable

The normalized ramp rate dependences of AC loss are shown in Fig. 5. All these dependences are stronger than those for MCA 17. Especially in the soldered cable, the losses for the perpendicular field increase very fast, and finally at 9.5 kG/sec, a flux jump was observed in the magnetization curve.

As mentioned in the previous section, this behavior is due to the eddy current between strands. As a proof of it, the ramp rate dependences of the unsoldered cable are much weaker than those of the soldered one. To check the above eddy current effect, the ramp rate dependences were measured for two different samples: one is a single strand wire and the other is the short soldered cable whose length is much shorter than the transposition pitch (now 0.5 inch ~1/4 x transposition pitch). For the latter one, the field was applied perpendicular to the flat face. The results are also shown in Fig. 5. The AC loss for the half inch long cable is decreased pretty much. This fact confirms the theoretical prediction(2) that the dominant eddy current is diamond shaped current, flowing horizontally without resistance in the superconducting wires and vertically through the contact resistance at the crossover points.

Increase of the loss of single strand with increasing $\dot{B}$ is is entirely due to the incomplete twisting of filaments inside the composite conductor. The rate dependence could be reduced by twisting more. We can easily estimate ρ_e from the doubling $\dot{B}$ of the single strand. Using this ρ_e, ρ_a can be derived in the same way as for MCA 17. These values are listed in Table II together with the doubling $\dot{B}$. The obtained values of ρ_e and ρ_a are reasonable, and almost in the same order of magnitude as those of MCA 17. Especially the value of ρ_a strongly depends on how well the strands are soldered together.

The maximum field dependences at constant ramp rate were measured for all the samples. All of them exhibit the same behavior, so the typical one is shown in Fig. 6. At around 2 kG, the dependence changes drastically. Below this field (B_s), the loss increases quadratic or cubic, and above that, almost linearly This behavior is peculiar to the multifilamentary twisted conductor and a reflection of the hysteresis loss in type II superconductors.

V. Conclusion

The soldered cable has a very large AC loss arising from the eddy current between strands, when the magnetic field is perpendicular to the flat face. The unsoldered one has a tolerable loss, but from a view point of mechanical and enthalpy stability, there may be some other problems.

References

1. Brechna: "Superconducting Magnet System", Springer-Verlang, N.Y.
2. M.N.Wilson: R.H.E.L./M/A/26 ('72)
3. C.R. Walters: BNL, AADD 74-2
4. C.P. Bean: Rev. Mod. Phys. 47 31 ('64)
5. R. Yamada, M.P. Price, H. Ishimoto: FNAL Internal Report TM-598, July 1975

Table I

	MCA 17	MCA 23
Outside Dimensions	50 x 240 mil	50 x 300 mil
No. of Strands	17	23
Filament diameter	7.9 μ	7.9 μ
Total No. of Filaments	39100	52900
Twist pitch (4ℓ)	.5 inch	.5 inch
Transposition pitch (4L)	1.6 inch	1.6 inch
Copper/super ratio	1.8	1.8
Normal/super ratio	3.1~3.4	2.7~2.8
Diameter of single strand	25 mil	25 mil
Aspect ratio (α)	5	6

Table II

		field orientation	$\dot{B}_d$ (kG/sec)	
MCA 17	Soldered	$\perp$	0.5	ρ_e $8x10^{-8}\Omega\cdot cm$
		$\parallel$	10	ρ_a $9.0x10^{-7}\Omega\cdot cm$
	Unsoldered	$\perp$	8.3	ρ_e $9x10^{-8}\Omega\cdot cm$
		$\parallel$	11	ρ_a $1.5x10^{-5}\Omega\cdot cm$
MCA 23	Soldered	$\perp$	0.15	ρ_a $3.8x10^{-7}\Omega\cdot cm$
		$\parallel$	0.8	
	Unsoldered	$\perp$	2.2	ρ_a $4x10^{-6}\Omega\cdot cm$
		$\parallel$	3.0	
	Single Strand	---	5.25	ρ_e $4.1x10^{-8}\Omega\cdot cm$

Measurements were done at B_{max} = 22.6 kG, so J_c was assumed to be $4x10^5 A/cm^2$.

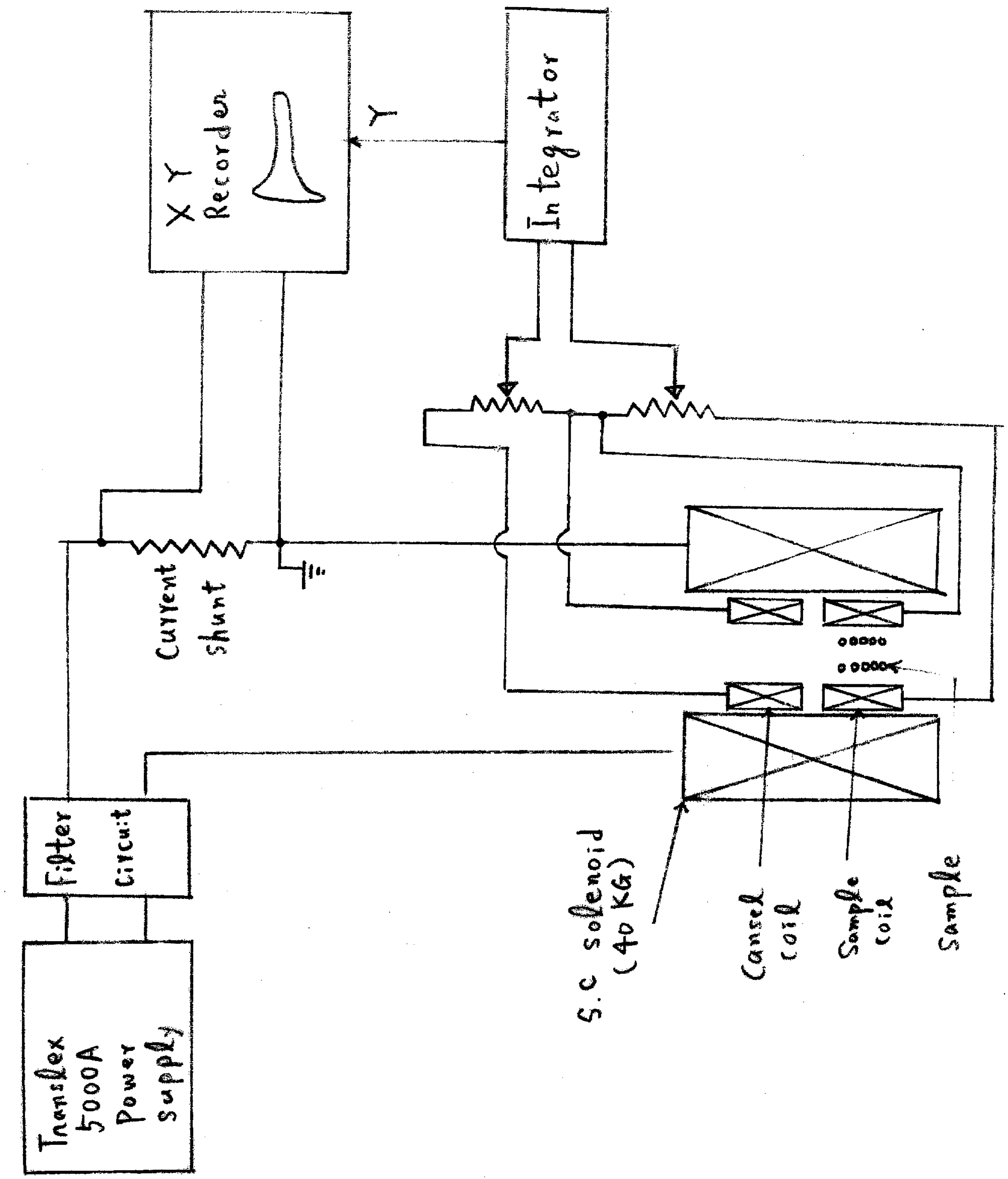


Fig. 1. Block diagram of Magnetization measurement

Fig.3 Maximum field dependence of J_c of McAl17 (unsoldered)

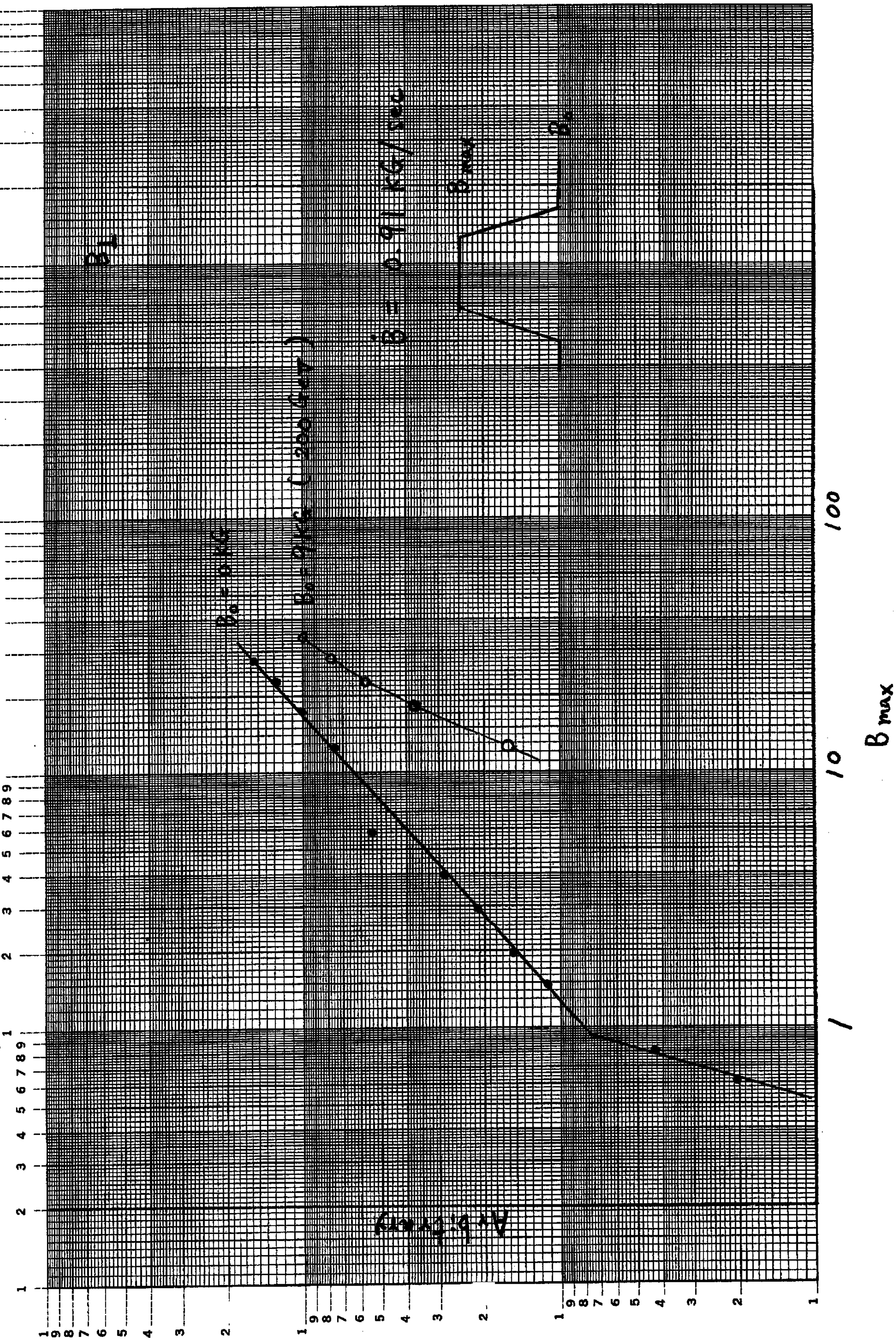
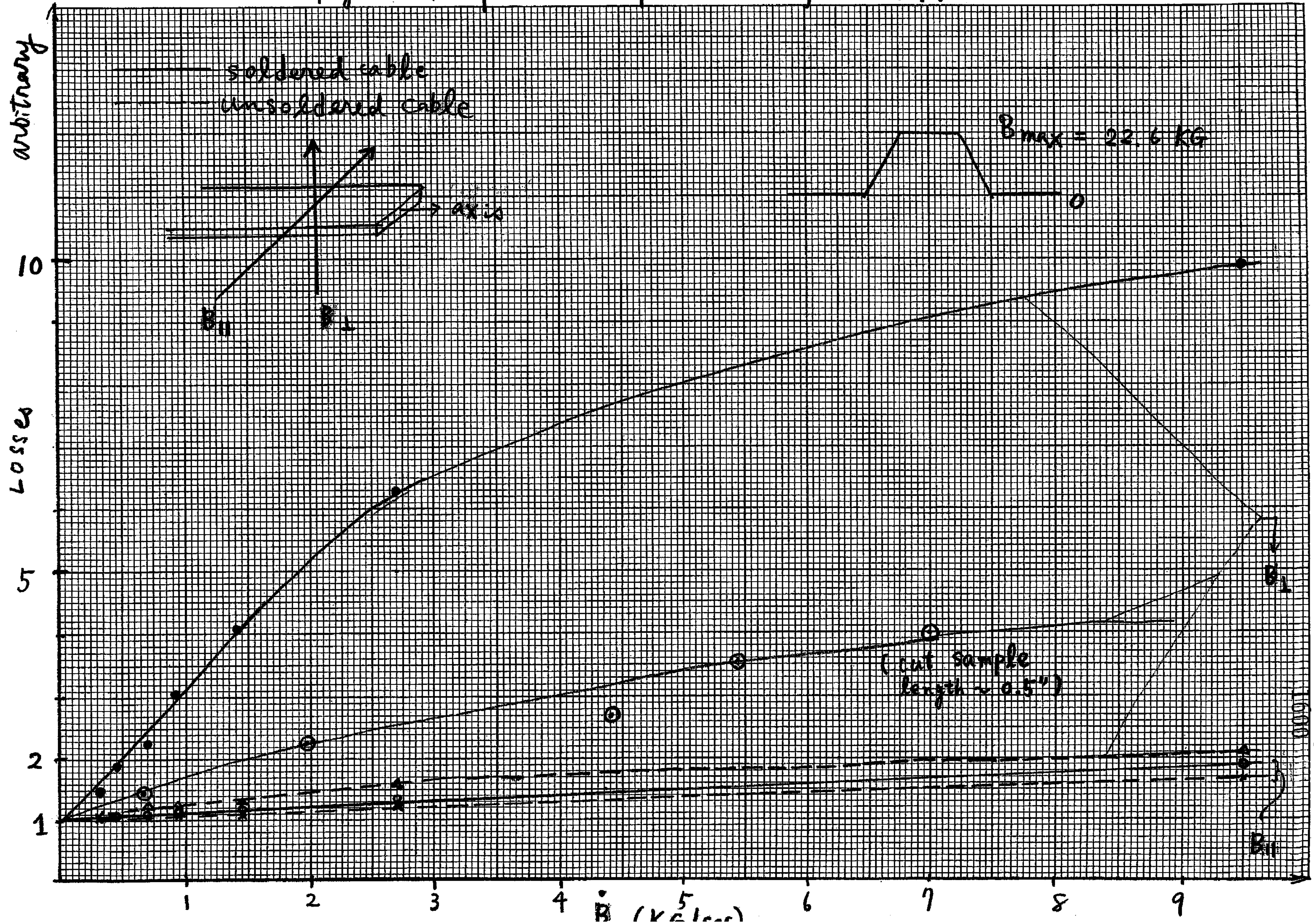


Fig. 2 Ramp rate dependence of MCA 17



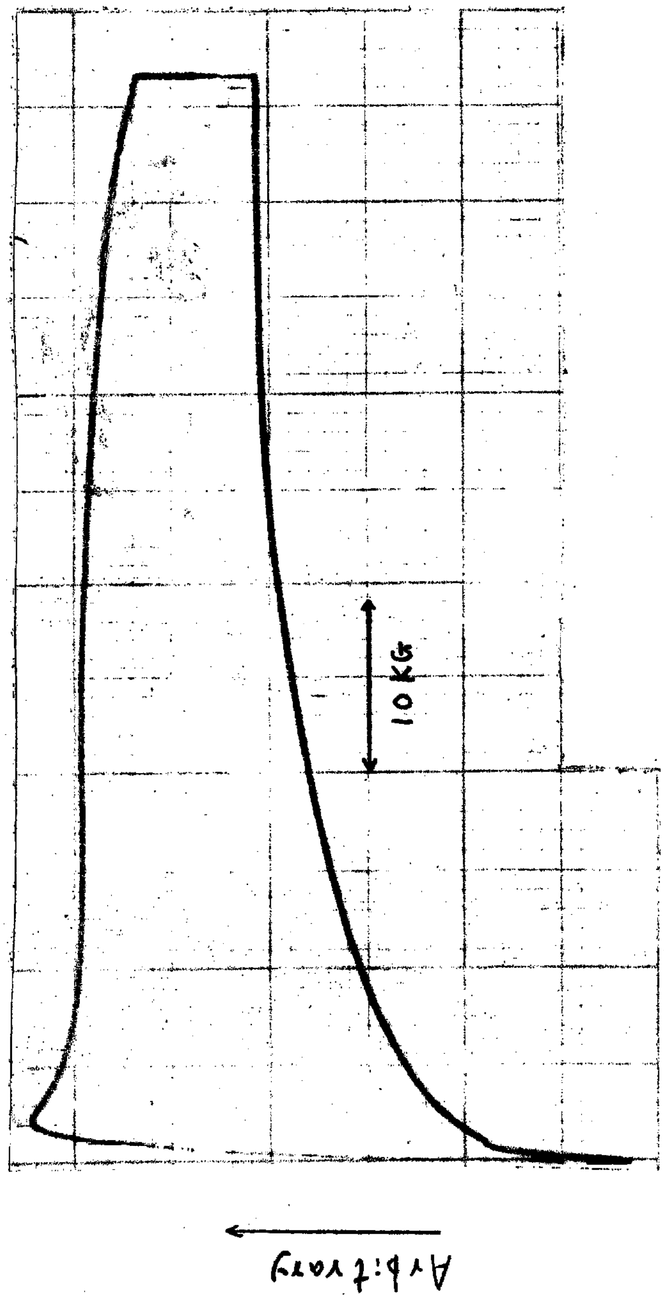


Fig.4. Magnetization loop of MCA 17 cable

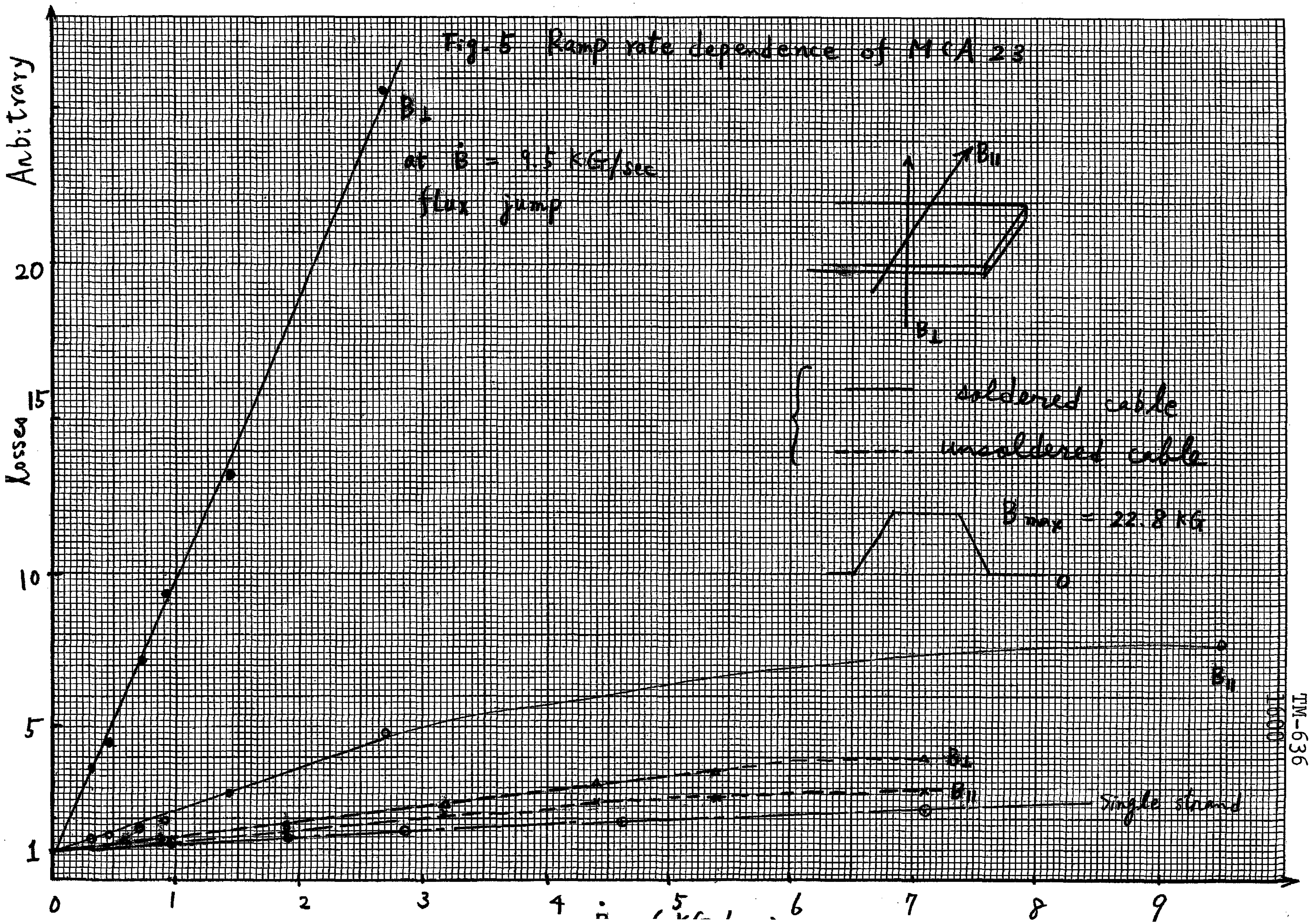
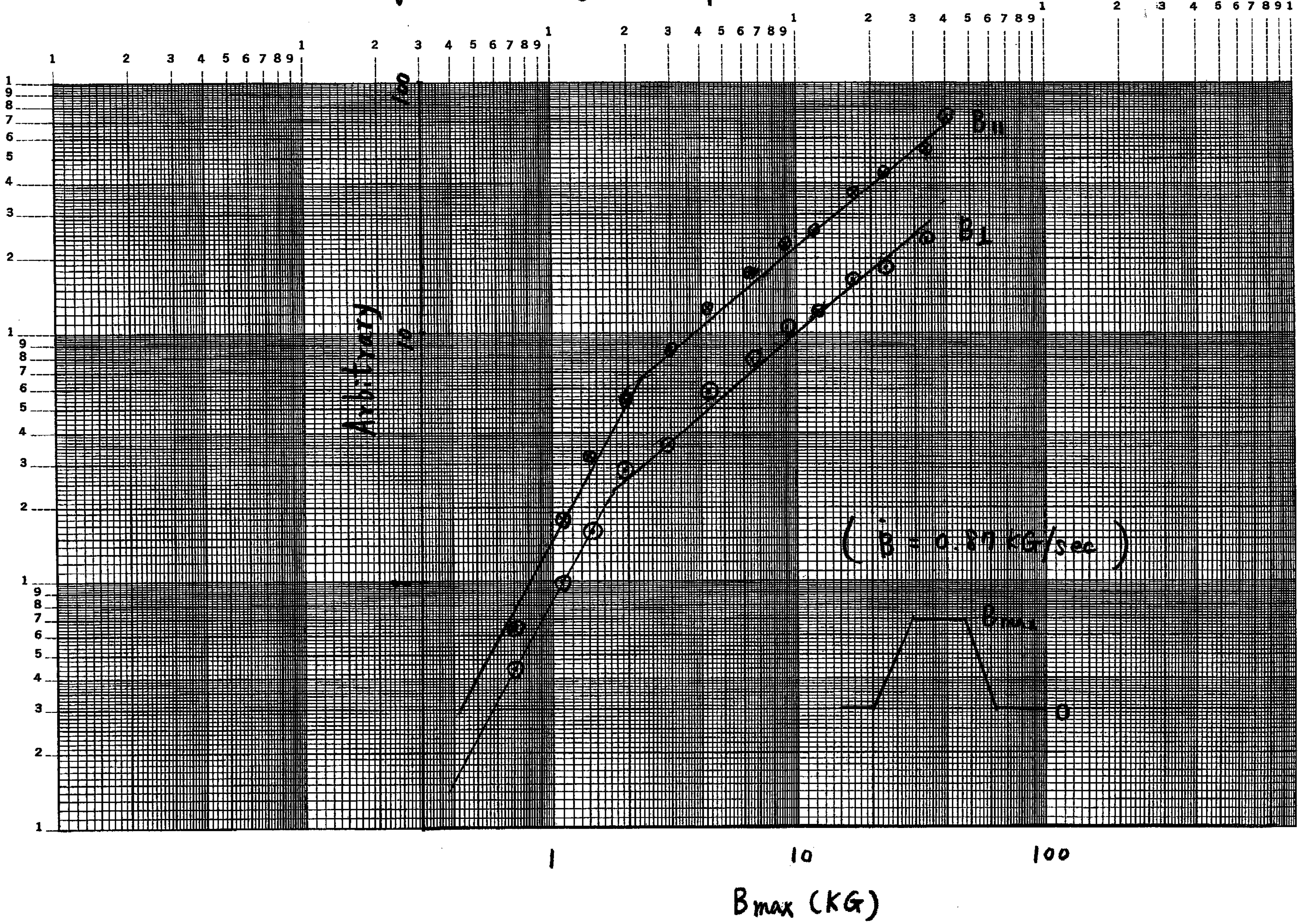


Fig. 5 Ramp rate dependence of MCA 23
$B_\perp$
at $\dot{B}$ = 9.5 KG/sec
flux jump
$B_{\parallel}$
$B_\perp$
soldered cable
unsoldered cable
B_{max} = 22.8 KG
0
$B_{\parallel}$
$B_\perp$
$B_{\parallel}$
single strand
Arbitrary
losses
20
15
10
5
1
0
1
2
3
4
5
6
7
8
9
$\dot{B}$ (KG/sec)

Fig. 6 Max. field dependence of MCA 23 (unsoldered)



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